Infrared Emission from the Radio Supernebula in NGC 5253: A Proto-Globular Cluster?

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ABSTRACT

Hidden from optical view in the starburst region of the dwarf galaxy NGC 5253 lies an intense radio source with an unusual spectrum which could be interpreted variously as nebular gas ionized by a young stellar cluster or nonthermal emission from a radio supernova or an AGN. We have obtained 11.7 and 18.7 μm images of this region at the Keck Telescope and find that it is an extremely strong mid-infrared emitter. The infrared to radio flux ratio rules out a supernova and is consistent with an HII region excited by a dense cluster of young stars. This "super nebula" provides at least 15% of the total bolometric luminosity of the galaxy. Its excitation requires $10^5 - 10^6$ stars, giving it the total mass and size (1-2 pc diameter) of a globular cluster. However, its high obscuration, small size, and high gas density all argue that it is very young, no more than a few hundred thousand years old. This may be the youngest globular cluster yet observed.

Subject headings: clusters: globular, formation—galaxies: starbursts, WR galaxies

1. Introduction

The dwarf I0/S0 galaxy NGC 5253 is an active star formation source, with abundant $H\alpha$ emission, WR stars, and many optically visible star clusters in the central 100 pc (Beck *et al.* 1996; Gorjian 1996; Calzetti *et al.* 1997). More than half the radio emission from this galaxy is found to come from an intense source of diameter 1.3 pc at 2 and 1.3 cm (for a distance of 4 Mpc), in the star formation region but not identified with any optical counterpart (Turner *et al.* 2000). Turner *et al.* (2000) called this source the radio supernebula; it has a brightness temperature of 10^4 K at 2 cm and an optically thick spectrum that is either flat or slightly rising. Extra-galactic radio sources of such high T_b and luminosity are usually non-thermal synchrotron sources with steeply falling spectra or AGN with flat spectra. Thermal radio sources, generally gaseous nebulae surrounding young stars (HII regions) have almost flat spectra, but are typically two to three orders of magnitude less luminous than this radio source. If this were an HII region it would require an extraordinarily high number of stars to excite the gas. If it were an non-thermal source it would also be extraordinary for its kind. From the radio emission alone, we cannot tell if this is an HII region, a supernova remnant (SNR), or an Active Galactic Nucleus (AGN).

We have therefore obtained high resolution images of the radio source in the mid-infrared, since an HII region will be a strong infrared emitter with a characteristic spectral energy distribution, different from a SNR or AGN. The observations and results are discussed in the next section, followed by our deductions as to the nature of the source and its properties.

2. Observations

The observations were made during the recommissioning of the Long Wavelength Spectrometer (LWS) (Jones & Puetter 1993) on the Keck I Telescope on Mauna Kea in March 1999. Two infrared images were obtained: one with a 1 μm wide filter centered at 11.7 μm and one with a 0.5 μm wide filter centered at 18.7 μm. Fluxes were calibrated by reference to the standard stars β Gem and α Boo and are estimated to have uncertainties of 10%. In Figure 1 we show the infrared color image superimposed on an optical photograph from the *Hubble Space Telescope* (*HST*), and in Figure 2 the individual 11.7 and 18.7 μm images. The registration uncertainty is limited by the *HST* image and is estimated to be $\sim 1''$.

The infrared source is barely resolved at a diameter of $0.58''$at 11.7 μm which is about twice the diffraction limit of the Keck. The source is $0.62''$, only 25% larger than the diffraction limit, at 18.7μm. These sizes may be upper limits to the true source size since at the time of the observations the telescope settle times had not been accurately determined and inadequate settle times may have broadened the images. There is no significant difference between the appearances of the source at the two wavelengths, and allowing for the differences in beam size the radio and infrared images agree. The source has 2.2 Jy total flux at 11.7 μm with S/N of 17 at the peak pixel and 2.9 Jy at 18.7 μm S/N of 12 at the peak. These agree with ground-based small-aperture fluxes (Lebofsky & Rieke 1979; Telesco, Dressel, & Wolstencroft 1993) as well as ISO-SWS data (Crowther *et al.* 1999). The IRAS satellite observed 2.6 Jy and 12 Jy at 12 and 25 microns, respectively, with beams that included the entire galaxy; this is a very bright and a very small infrared source.

3. The Infrared Source

3.1. What is It?

There are, as we stated above, three possible sources of the strong rising-spectrum radio emission from NGC 5253: an HII region, a SNR, or an AGN. The discovery that the radio source is also a strong mid-infrared emitter narrows down the possibilities. First, it rules out the presence of a bright radio supernova; supernovae are not significant mid-infrared sources. Most Galactic SNR are not detected at all in the IRAS bands (Arendt 1989). It has been suggested (Shull 1980) that a supernova explosion inside a dense molecular cloud will be very bright in the infrared, but that is calculated to be a short-lived stage, with the emission declining significantly on a time scale of a few years (Weiler *et al.* 1986). The agreement of our measurement with the IRAS fluxes from 1983 and the ground based work from 1972 (Rieke & Low 1972; Lebofsky & Rieke 1979; Telesco, Dressel, & Wolstencroft 1993) argues against this model.

The possibility that the source is an AGN cannot be excluded so decisively, because AGN show such variation in their infrared and radio properties. AGN are not themselves expected to be strong infrared emitters, although their spectra will depend on the amount and distribution of the dust nearby. Much of the observed range is probably due to the presence of both non-stellar central engines and starbursts in the same galaxy, and usually in the same nuclear region of the galaxy. NGC 1068 is the best-known example of a galaxy with both an AGN and a powerful starburst which can only with difficulty be separated. The high spatial resolution of our observations and the closeness of NGC 5253 will however challenge any model which tries to combine an AGN and a starburst in the radio-infrared source. The conclusive test for the presence of an AGN is spectroscopic, not photometric, and depends on the detection of fast moving gas near the central engine. That the gas studied optically in NGC 5253 does not have broad lines is not relevant to the gas in the radio source, which must be heavily obscured as it is 70 times brighter than one would predict based on the $H\alpha$ line (Calzetti *et al.* 1997). The only spectroscopic information currently available on the gas inside the radio and infrared source is the 10.5μm [SIV] line (Beck *et al.* 1996), which is no more than 60 km s^{-1} wide. Those observations cannot completely rule out a very weak plateau, as from a weak AGN. Another regime in which the influence of an AGN is usually strong is the X-ray: the X-ray spectrum and luminosity of NGC 5253 is perfectly consistent with a starburst in a clumpy medium (Martin & Kennicutt 1995). In short, while a small and quite unusual AGN could perhaps be hidden in NGC 5253, it would be very artificial; there is nothing in the data that needs or suggests one.

The final possibility, which the data strongly favor, is that the source of the infrared and radio emission is an HII region ionized by thousands of young stars. We presented this model in Turner *et al.* (2000) based on the radio data alone. The high mid-infrared fluxes of the NGC 5253 source, which exclude SNR and go far to exclude AGN, are perfectly consistent with the spectral energy distribution of an optically obscured HII region. The ratio of 11.7μm flux to the thermal radio flux is 180, a factor of 4.5 higher than would be expected from pure $Ly\,\alpha$ heating (Ho *et al.* 1990) and in agreement with results from many other star formation regions, Galactic and extra-Galactic. The observed ratio in starburst galaxies is usually in the 120-250 range.

The model that the NGC 5253 source is an optically obscured HII region fits *all* the data at hand: the radio spectrum, which is optically thick at 6 and probably 2 cm (Turner *et al.* 1998, 2000), as are dense and compact HII regions, the infrared flux and its ratio to the radio emission, the infrared lines which agree with the radio continuum (Beck *et al.* 1996), and the great excess of infrared and radio strengths over that predicted from the optical. The NGC 5253 source could be a compact HII region such as W51 or K3-50 writ large, except that Galactic compact HII regions typically contain 1 bright star in 0.01 pc diameter; the NGC 5253 source must hold not one OB star but a populous cluster. The ionization requirements of the super nebula are immense, $4\times10^{52}sec^{-1}$. The stellar population and density which are calculated in Turner *et al.* (2000) for a range of IMFs are accordingly high: 2×10^5 to 2×10^6 stars and 5×10^5 to 10^6 $M_\odot$ within a 1-2 pc region. The source requires not just a cluster of stars, but a large cluster with the stellar density, the size, and luminosity of a bright globular cluster.

3.2. On the Spectral Dominance and Spatial Concentration of the Source

The NGC 5253 super nebula is not only remarkable in itself; it dominates the galaxy's total spectrum to an astonishing degree. 80-90% of the total galactic flux in the 12 micron bands comes from this 1-2 pc region. NGC 5253 as a whole is rather blue in the infrared: it is stronger at 60μm than at 100μm and its νF_ν peaks at 25μm; a significant fraction of the flux at 25μm may be due to a silicate emission feature (Crowther *et al.* 1999). The supernebula has been imaged in only two bands, but also appears extremely blue, with a deduced dust temperature (for $\beta = 1.5$) of 180 K, consistent with the ISO mid-infrared spectrum (Crowther *et al.* 1999). We do not know what the supernebula contributes at 60 and 100μm, but even in the most extreme case that it contributes *nothing*, it would still provide about 20-25%, or 4×10^8 $L_\odot$, of the total flux emitted in the IRAS bands, which constitutes 75% of the total bolometric luminosity (2.4×10^9 $L_\odot$), radio to X-ray, of the galaxy. We note that the population of O stars required for the radio emission from the supernebula (Turner *et al.* 2000) will have a total luminosity of $0.8-1.2\times10^9 L_\odot$, compared to $1.8\times10^9 L_\odot$ which is the total infrared luminosity of the galaxy, as determined from IRAS fluxes by the prescription of Sanders & Mirabel (1996). This argues that all the infrared is distributed at the shorter wavelengths and that the super nebula gives at least half of the total IR luminosity, and potentially as much as two-thirds, in an infrared-dominated galaxy. So this giant HII region, less than 2 pc in diameter, may well dominate its host galaxy as thoroughly as does a bright AGN. NGC 5253 is the best example so far of the trend (Ho *et al.* 1990) that the bulk of the infrared emission in starburst galaxies is usually found in a much smaller volume than the IRAS beams, and implied by the finding (Bryant & Scoville 1999) that the molecular clouds which are the fuel of star formation are concentrated in small active regions.

4. A Very Young Star Cluster and its Problems

If, as we have argued, the radio-infrared source is a super nebula or giant HII region ionized by thousands of young O stars, conditions in the source must be extreme. If we adopt a total population of 10^6 stars (Turner *et al.* 1998, 2000) and a diameter of 1.5 pc, then the stellar separation is $\sim$0.02 pc. While such conditions in the cluster seem strange they are actually what would be expected from a just-formed or still forming super star cluster or globular cluster. At present the gas density in the cluster is high, 4×10^4 cm^{-3}, as deduced from the high radio optical depth (Turner *et al.* 2000) and there is enough dust in the region to obscure the optical emission completely. As the stellar activity continues the gas and dust may be expected to disperse, weakening the radio and infrared emission and permitting the cluster to be seen in the visible, which will then resemble super star clusters which are commonly seen in starburst regions.

We argue that the source is excited by a very young super star cluster, large enough to become a globular cluster; just how young? Since we do not see the stars we cannot find their ages directly. The age of the nebula is limited from its dynamical lifetime, which must be short. The gas in the nebula, which is at $\sim 10^4$ K, will be overpressured relative to the density and temperature of a normal ISM and will expand at the sound speed, roughly 10 km s^{-1}, so the observed supernebula should double its size in $\sim 1.5 \times 10^5$ years.

The problem of lifetimes, reviewed in Kurtz *et al.* (2000), haunts the study of the Galactic ultra-compact HII regions that these young star clusters so resemble. Galactic ultra-compact HII regions are thought to be older than their dynamical ages, since the dense and clumpy molecular cloud environment of these sources slows their expansion and extends their lifetimes. In NGC5253 there is no evidence for confinement by molecular gas: in fact, no CO is detected within 200 pc of the nebula (Turner, Beck, & Hurt 1997; Meier, Turner, & Beck 2000). Even at the low metallicity of NGC 5253, CO should be easily detectable based on L_{IR}. Another way to confine the nebula is with the $B^2/8\pi$ pressure of the magnetic field, which will become comparable to the thermal pressure of the NGC 5253 nebulae for B fields of a few milligauss. The B field strength in selected locations of NGC 5253 was estimated from minimum-energy arguments to be 5-7 milligauss (Turner *et al.* 1998), high for a galaxy but typical of a dense star-forming molecular cloud (Zweibel 2000), and large enough that it may be important in the pressure balance of the nebula. Finally, the cluster is so massive and compact that it is not inconceivable that the nebula is actually gravitationally bound, in spite of the large pressure gradient.

The question of the lifetimes of the earliest and most obscured stages of star formation will become increasingly important as more of these very young sources are observed on scales from the Galactic Ultra-compact HII regions to the proto-globular cluster in NGC 5253. In fact, luminous obscured infrared bright sources have been seen in the Antennae, although larger (50 pc) than the supernebula (Mirabel *et al.* 1998); and compact luminous IR sources similar to the supernebula have been seen in NGC 253 (Pina *et al.* 1992; Keto *et al.* 1993). Both of these galaxies also have large numbers of young super star clusters (Watson *et al.* 1996; Whitmore *et al.* 1999). High resolution radio images of other galaxies like He 2-10 (Kobulnicky and Johnson 1999; Tarchi *et al.* 2000) are also revealing possible candidates. There actually may be many of these young sources yet to be discovered by high resolution infrared observations.

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Fig. 1.— The infrared color image obtained from the 18.7 and 11.7 micron images, superimposed on the optical HST image. The width of the inset is $5.5''$.

Fig. 2.— The left image is the 11.7 micron image and the right image is the 18.7 micron image from LWS on Keck I. The width of each image is $10''$.